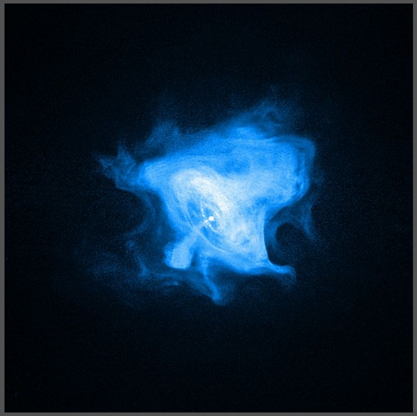
The 'absolute' timing of the Crab pulsar at high-energies



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using Fermi LAT, INTEGRAL ISGRI, XMM-Newton EPIC-pn and RXTE PCA data [Fermi GBM NaI]

Jodrell Bank radio observations: our baseline

- Daily monitoring of the Crab pulsar (P ~ 33 ms) started 31 years ago with 42 Ft telescope at 610 Mhz
- Arrival time delay : $t_{arr} \sim DM/\nu^2_{obs}$
- DM variations due to nebular plasma fluctuations
- Occasionally observations at 1400-1700 Mhz with larger Lovell telescope to constrain DM=DM(t)
- Before Dec-2011: DM = c
  After : DM = c + dDM/dt x t
- Timing parameters (on monthly base) stored at JB database: pulse freq. and its first two time derivatives at epoch t_0

Crab pulsar (PSR B0531+21) as timing calibration target for HE-instruments

- INTEGRAL ISGRI: Revs. 47-1736 (up to 14/10/2016)
  (20-100 keV; 61 μs; using revised Time Correlation files as of late 2007 i.e. correcting for 47 μs REDU gs offset; using measured orbit in propagation delay)

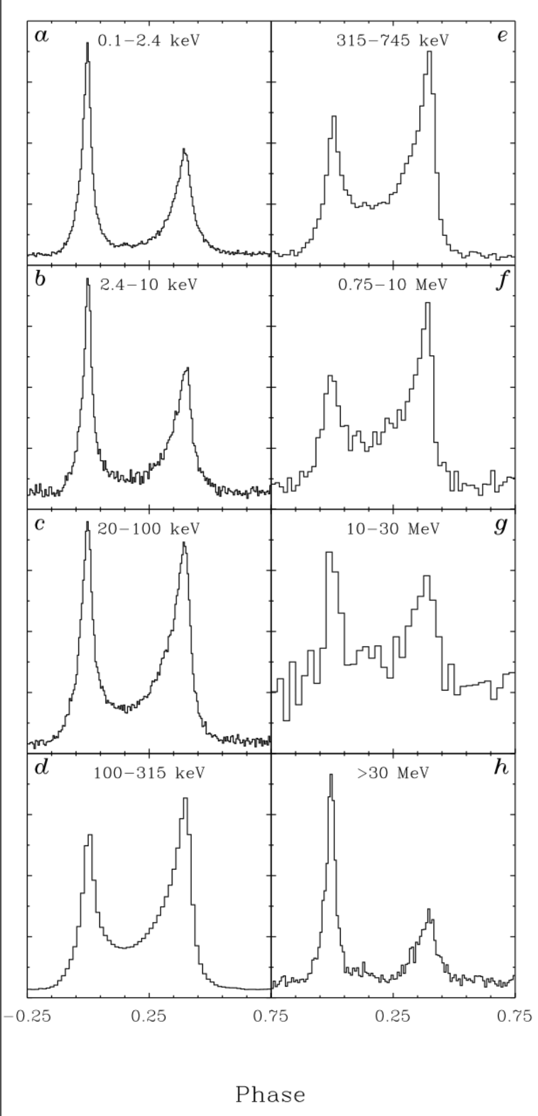
- XMM-Newton EPIC-pn Timing & Burst Mode
  (2-10 keV; 30 μs (TM), 7 μs (Bu))

  XMM launch - Oct. 2016

- Fermi LAT: Aug. 2008 – Sept. 2016
  (>100 MeV; 1 μs)

- RXTE PCA: INTEGRAL launch – Dec. 2011
  (2-32 keV; 1 μs (Good Xenon modes), but Crab obs. in event mode with 250 μs

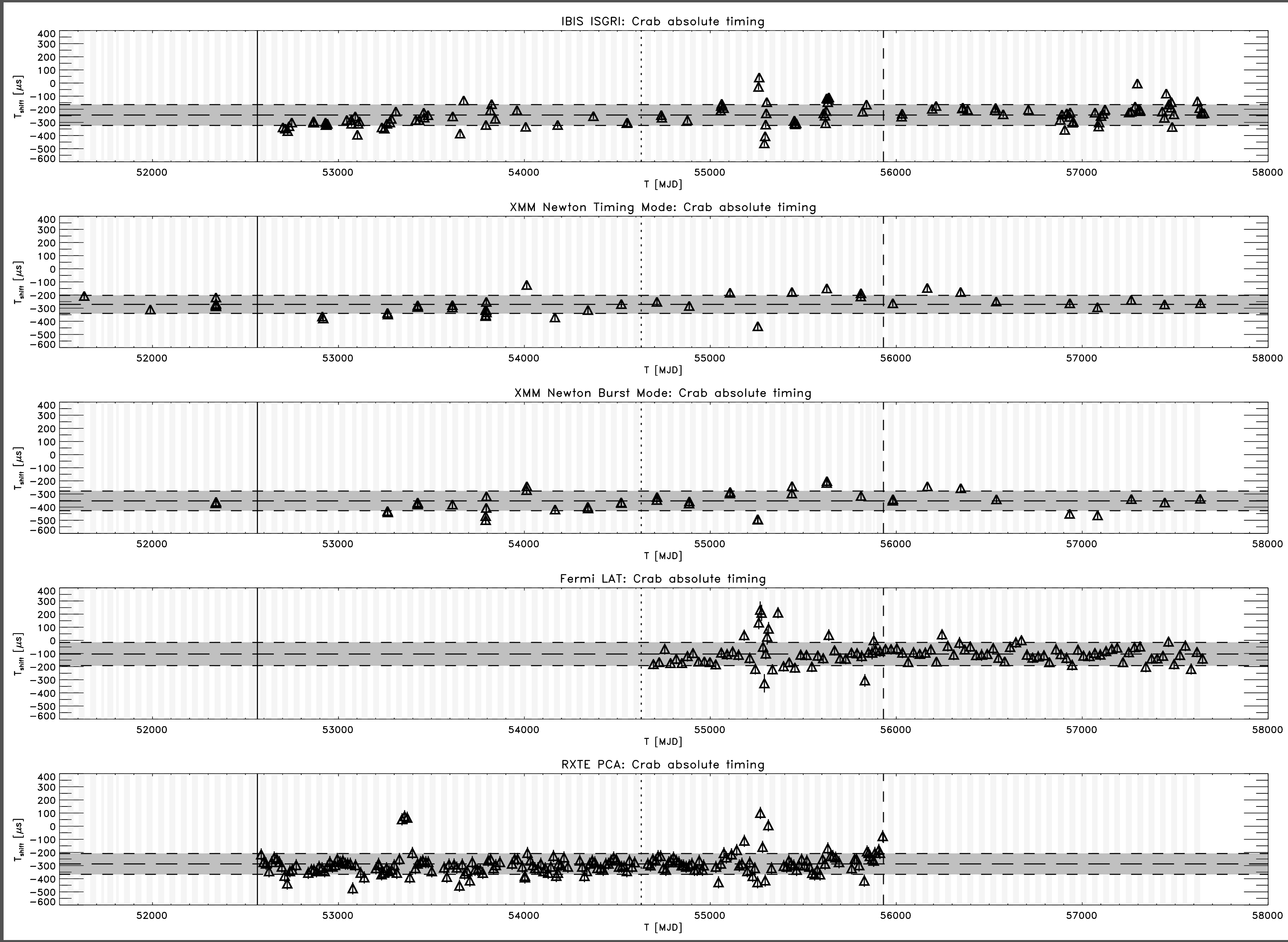
  (decommissioning in Jan. 2012)



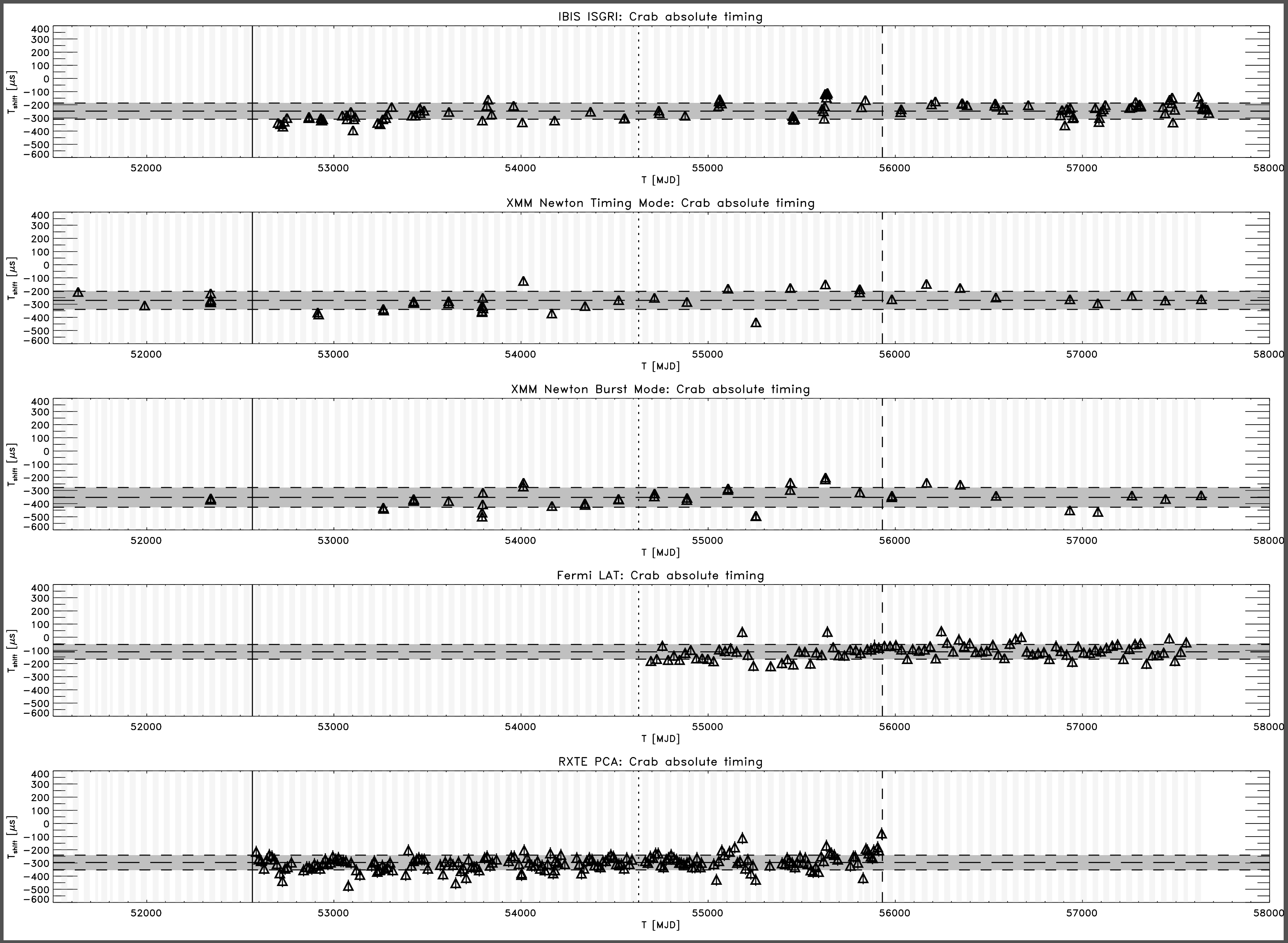
Barycentering (barycen, gtbary, faxbary), epoch folding and correlation etc. processes all use equivalent procedures!

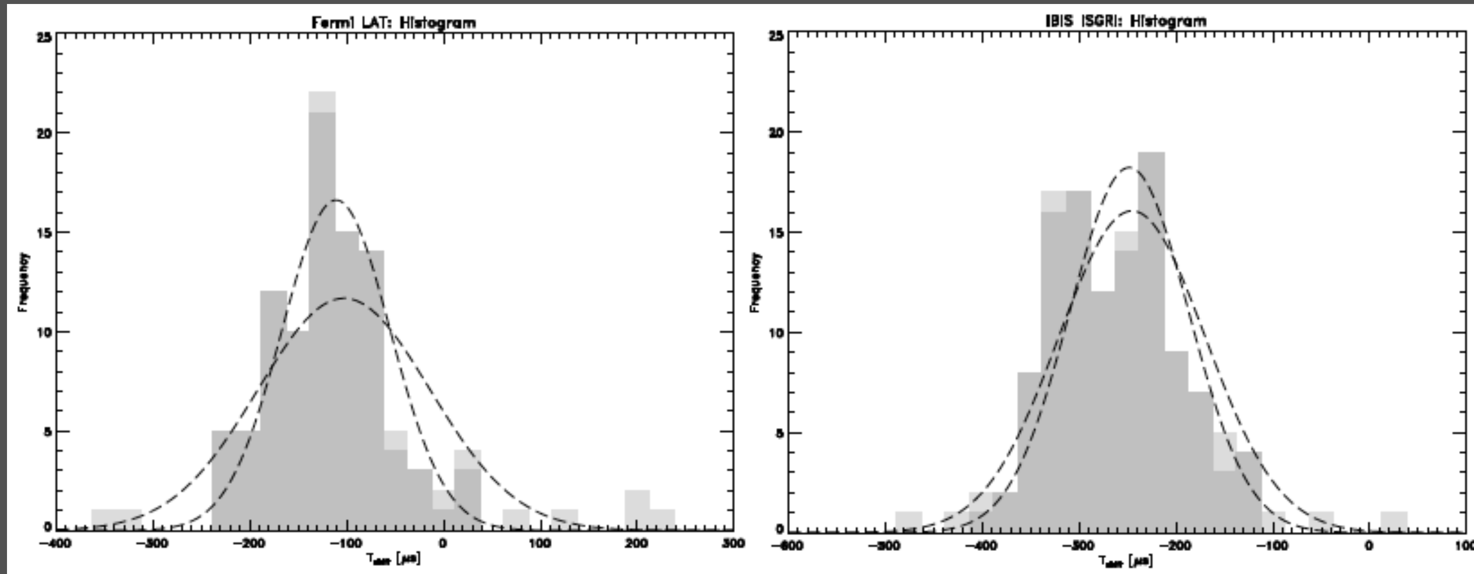
SRON

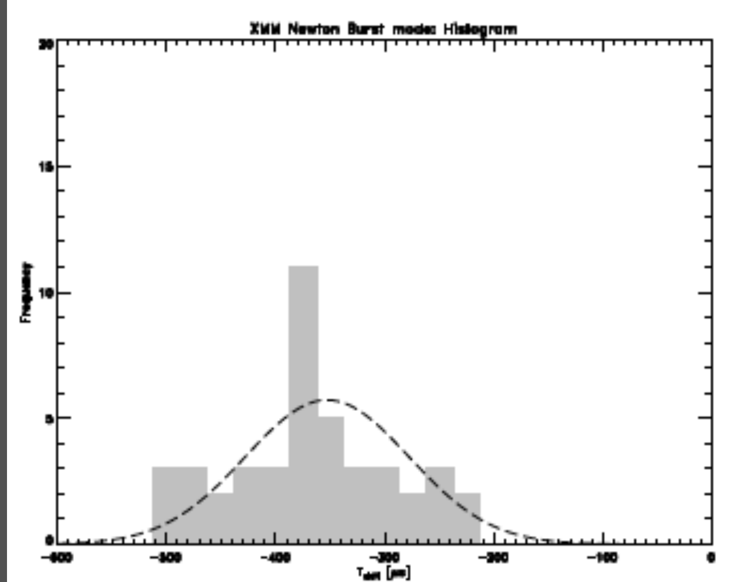
Absolute timing: All measurements



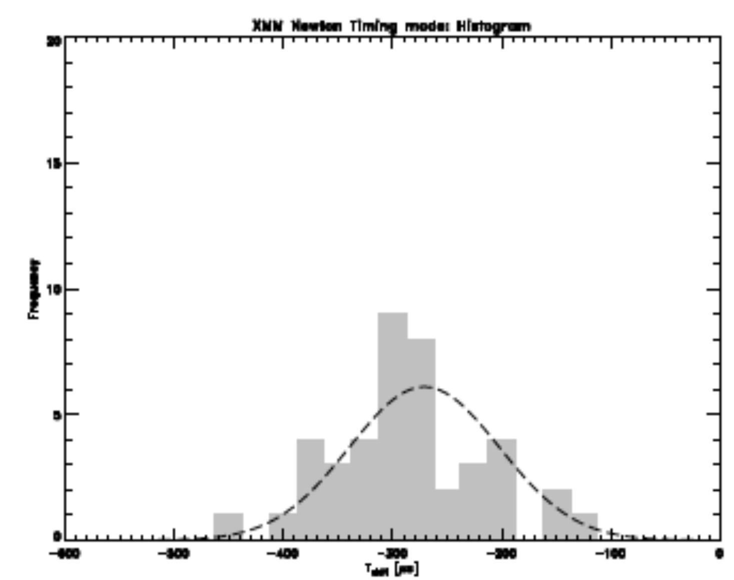
Absolute timing: Measurements minus outliers







(a) XMM Newton EPIC PN Burst mode



(b) XMM Newton EPIC PN Timing mode

Instrument	τ (μs)	$\Delta\tau$ (μs)	σ (μs)	$\mathcal{S}$	$\mathcal{K}$	n
Fermi LAT						
With outliers	-104	±4	±88	1.4±0.2	3.8±0.5	107
Without outliers	-111	±4	±57	0.5±0.3	0.2±0.5	93
XMM Newton EPIC PN						
Burst mode	-353	±4	±75	-0.1±0.3	-0.6±0.7	43
Timing mode	-271	±4	±69	0.1±0.4	-0.3±0.7	42
Burst + Timing mode	-312	±3	±83	-0.1±0.3	-0.3±0.5	85
INTEGRAL IBIS ISGRI						
With outliers	-245	±2	±76	0.5±0.2	1.2±0.4	122
Without outliers	-248	±2	±61	0.1±0.2	-0.7±0.5	112
RXTE PCA						
With outliers	-288	±3	±79	2.0±0.2	7.7±0.3	205
Without outliers	-297	±3	±56	0.1±0.2	1.5±0.3	197

Table 4.1: Time shift (τ), uncertainty ($\Delta\tau$), standard deviation of the distribution (σ), skewness ($\mathcal{S}$), kurtosis ($\mathcal{K}$) and the number of measurements (n).

Distribution widths: ~60 μs ! (XMM-Newton ~10-15 μs wider)

$$\sigma_M^2 = \sigma_I^2 + \sigma_{JBO}^2$$

Peak-to-peak uncertainty t_{acc} of Jodrell Bank (radio) arrival times

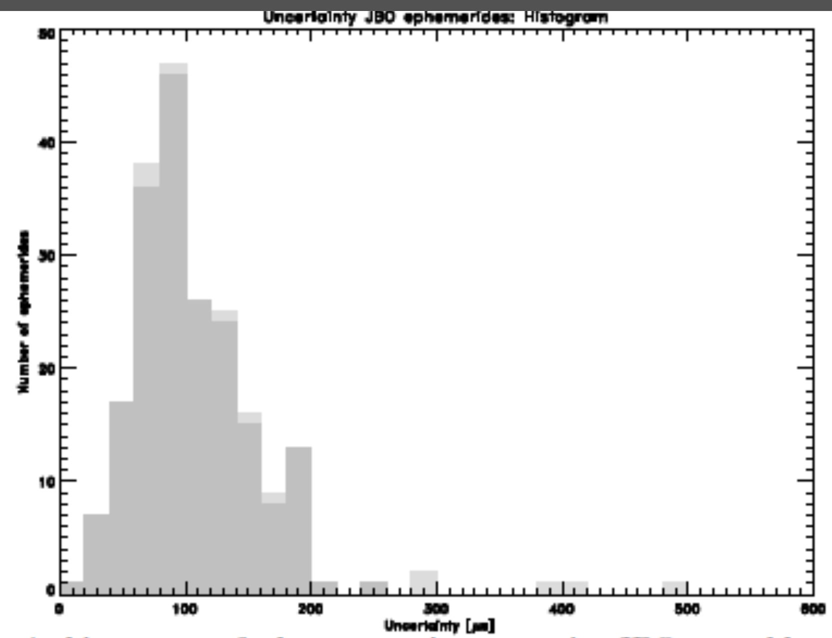


Figure 4.7: A histogram of the uncertainty t_{acc} in JBO monthly Crab pulsar ephemerides. Uncertainties without outliers are coloured dark-grey. Outliers are colored light grey. 3 outliers have an uncertainty of more than 600 μs and are outside the plot range of this figure.

Average t_{acc} : 118 ± 43 μs ➔
For sinusoidal variations, RMS or σ_{JBO} = 118 / 2√2 ~ 42 ± 16 μs

Thus, σ_M reflects for a significant part the uncertainty in σ_{JBO}

(σ_I = 35 ± 20 μs)

Instrument related notes: INTEGRAL ISGRI

- Updated time delay Δt = -248 ± 2 μs is consistent with earlier value of -285 ± 12 μs (Kuiper et al. 2003), taking into account the 47 μs REDU ground station error

- Since 26/11/2012 Fermi GBM NaI/BGO in TTE mode i.e. 2 μs accuracy (GPS synchronized / s) in 128 chan.

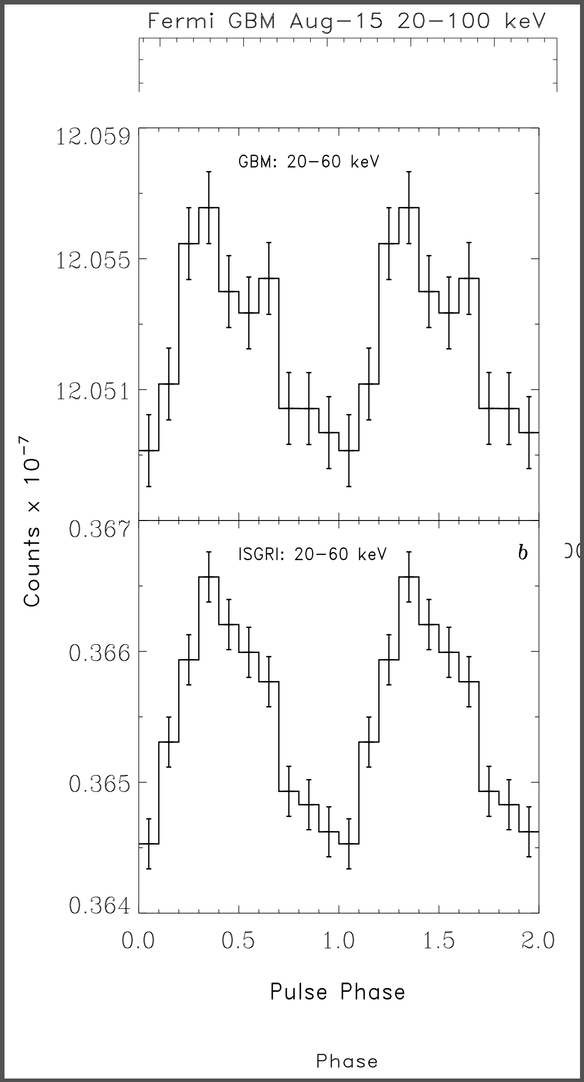
  Comparison ISGRI/NaI Aug-2015 data yielded:

  $\Delta t_{GBM\text{-}ISGRI}$=+26.3 ± 6.4 μs

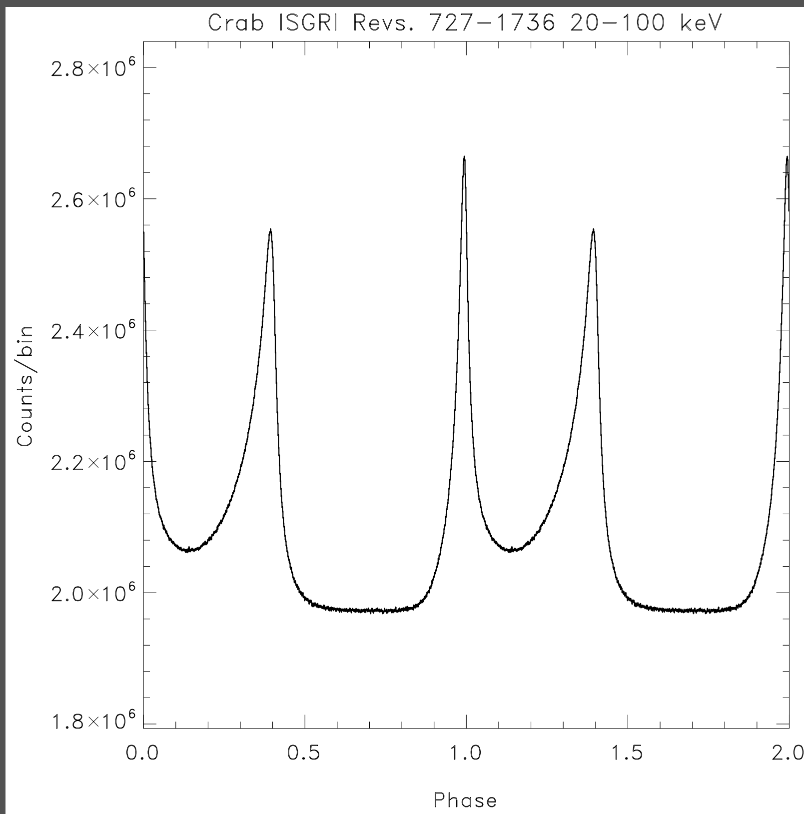
  (GBM a bit ahead)

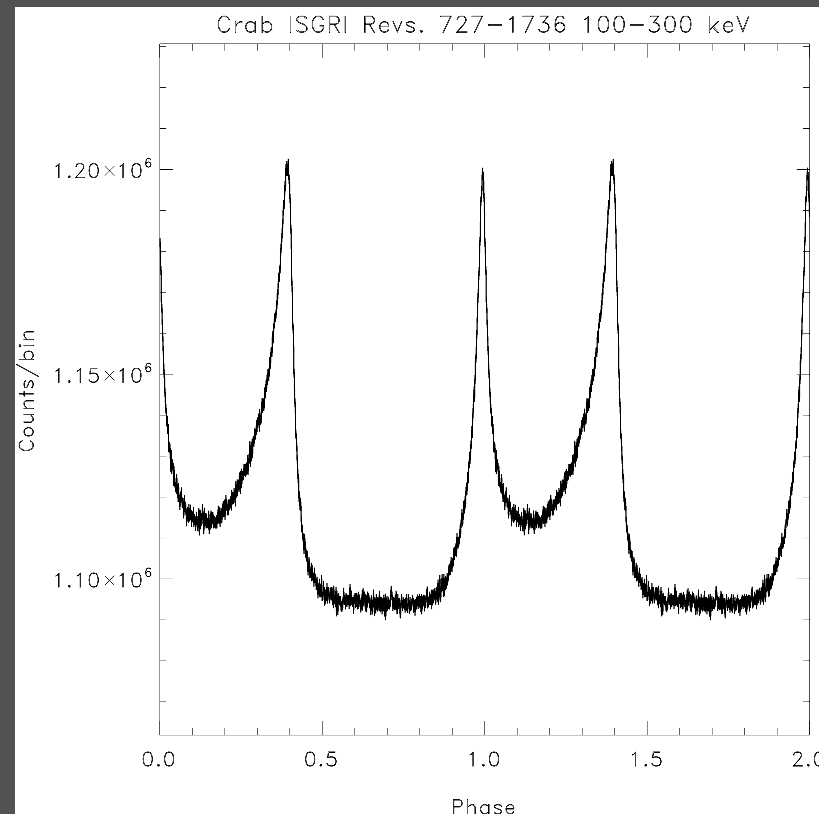
- Comparison using the (transitional) ms-pulsar IGR J18245-2452 (P=3.9 ms) in M28 during April 2015 outburst yielded +23 ± 109 μs

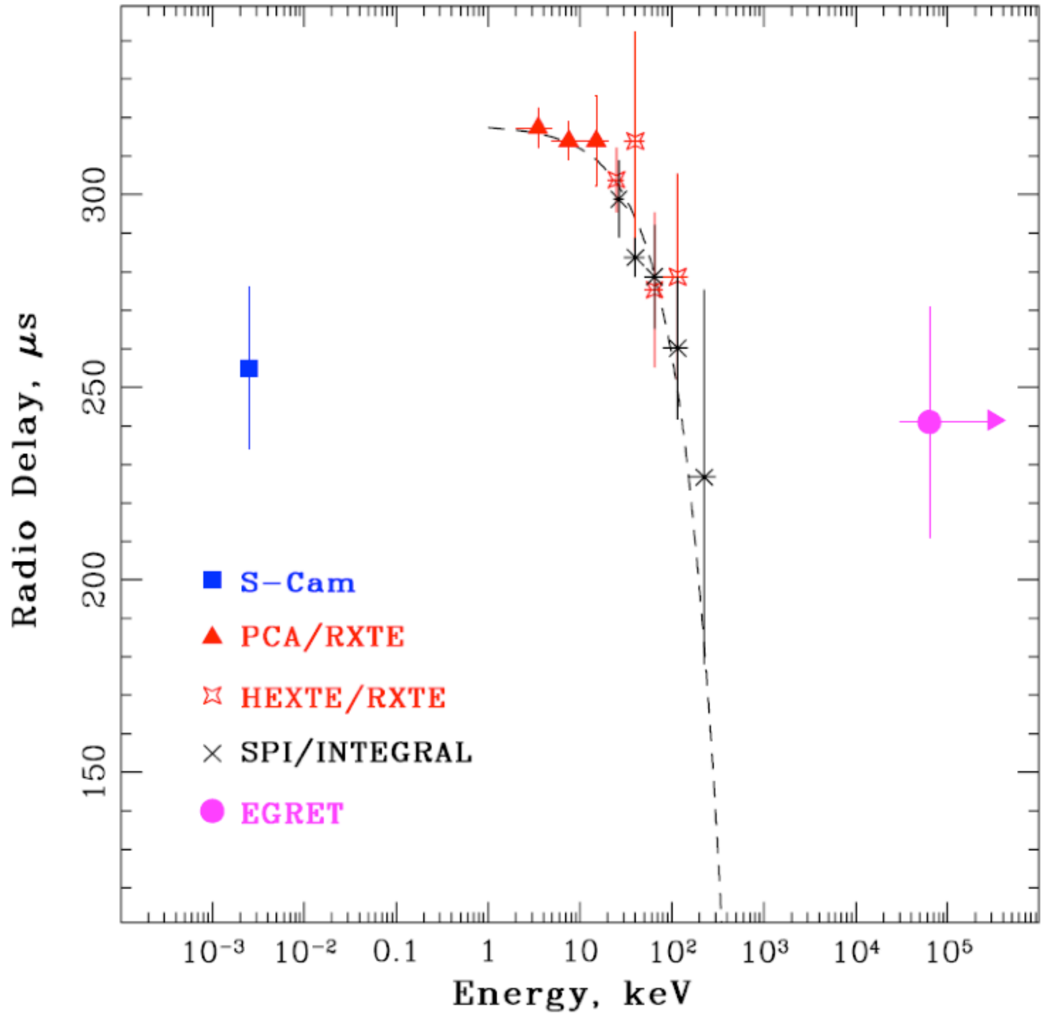
- Ground segment MOC does / has done great job!



Astrophysical result using ISGRI: shift between 20-100 keV and 100-300 keV profiles is only 4.9 ± 1.4 μs (Revs. 727-1736 combination; 720 bins), NOT following the trend seen (suggested) by Molkov et al. (2010), ApJ 708, 403 based on SPI data






Radio Delay, μs
300
250
200
150
S−Cam
PCA/RXTE
HEXTE/RXTE
SPI/INTEGRAL
EGRET
10⁻³
10⁻²
0.1
1
10
10²
10³
10⁴
10⁵
Energy, keV

Instrument related notes: Fermi LAT

- Abdo et al. (2010) ApJ 708, 1254 reported a delay -281 ± 12 ± 21 μs
- We report a delay of -111 ± 4 μs (8 years of LAT data) ….
- The Veritas collaboration reported in Sci. 334, 69 (2011) a corrigendum of the LAT result: -138 ± 12 ± 21 μs (Aug. 08 – Apr. 09)

  We found for same period : -141 ± 4 μs , now consistent!

Instrument related notes: XMM-Newton

- The delays measured in TM and Bu mode differ significantly: 82 μs

  Do NOT mix TM and Bu mode data!
- Some XMM obs. are excluded due to (uncorrectable) frame (?) jumps
- Distributions wider
- Pile-up in TM – mode (especially during the Fall observations)
  Much better calibration source is ms-pulsar PSR B1937-21

In future: Combined radio / Fermi LAT ToA analysis will enable proper DM modelling ➔ more accurate timing models!